Short-Pulse Dense Wavelength-Division-Multiplexed Optical Interconnects

David A. B. Miller and James S. Harris Jr.

Stanford University

http://ee.stanford.edu/~dabm

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
18 APR 2000	**N/A**	**-**

4. TITLE AND SUBTITLE	
Short-Pulse Dense Wavelength-Division-Multiplexed Optical Interconnects	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Stanford University**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
DARPA/MTO, WDM for Military Platforms Workshop held in McLean, VA on April 18-19, 2000, The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**UU**	**31**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Summary

WDM interconnects between silicon chips

- short-pulse WDM
- dense receiver/transmitter arrays

Synchronization with short pulses

- data resynchronization
  - *skew and jitter removal*

Ultrafast optoelectronic gate

- possible time-division demultiplexing and wavelength conversion component,
  - *controllable by electronics*

GaInAsN for high uniformity long-wavelength devices

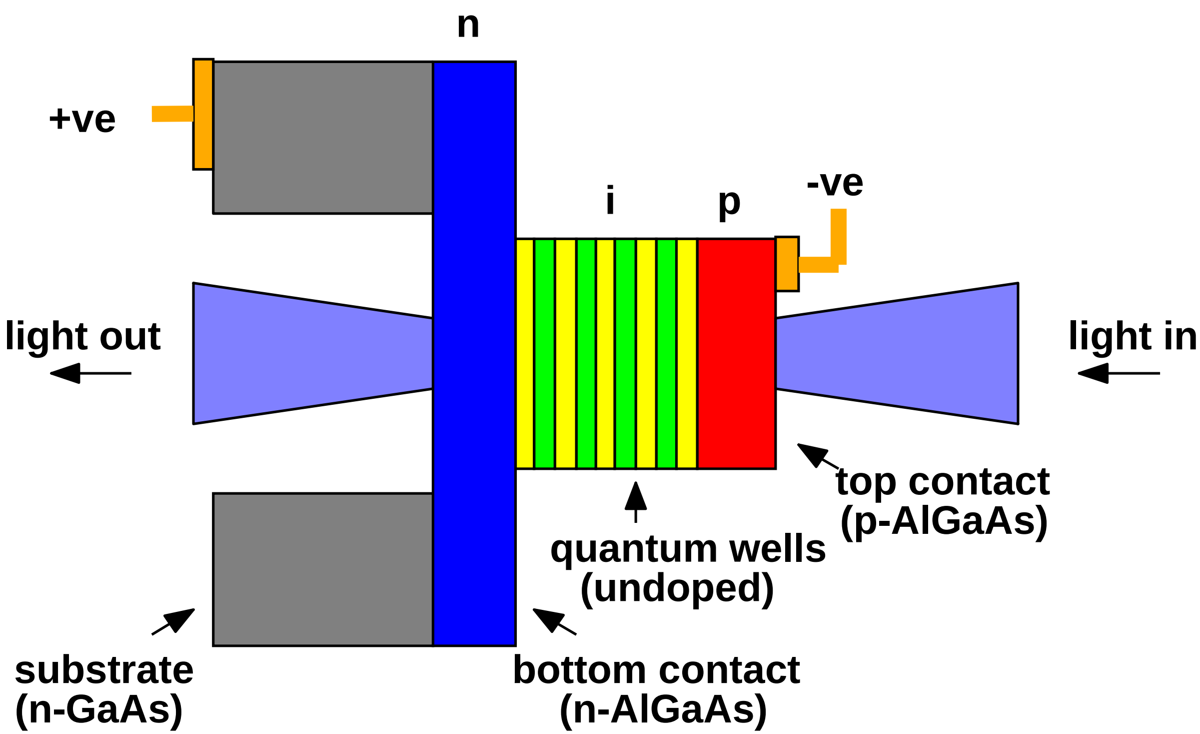
- unity sticking coefficient of N should allow high uniformity devices for long wavelengths
- potentially usable in long wavelength WDM systems

Modulator-Based Interconnects

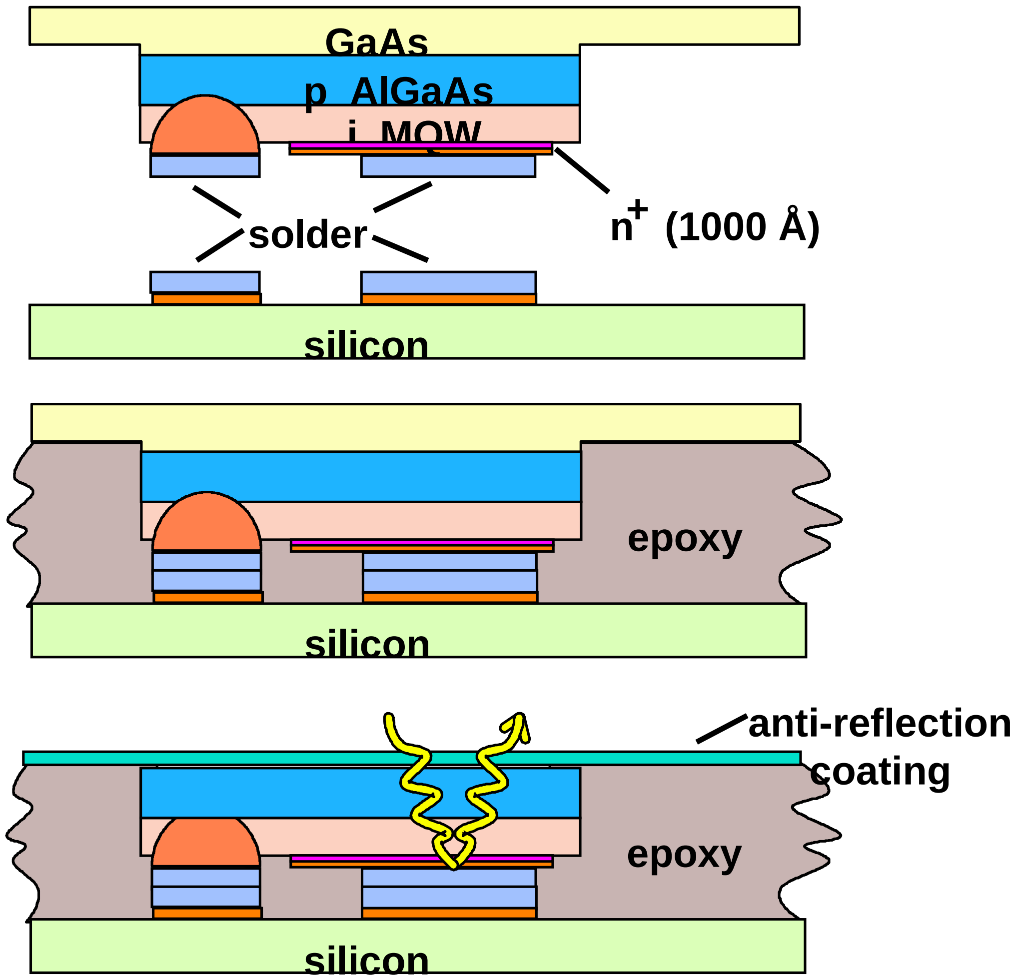
quantum well reflective modulators

- **solder bonded to silicon integrated circuits**
- **can function either as photodetector or output modulator (depending on circuit)**
- **can be made successfully in large numbers**
- **can be used with short pulse sources**
- **can be used with WDM sources (usable range ~ 6 - 10 nm)**

Quantum Well Modulator

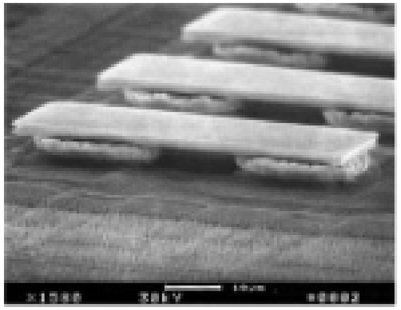


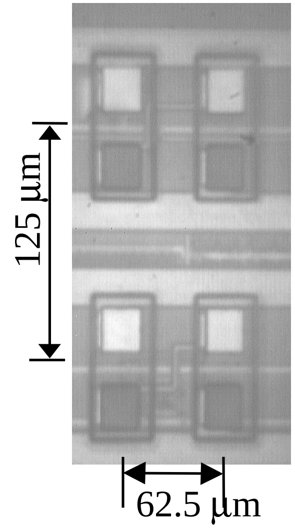
Quantum Well Modulators Solder-Bonded to Silicon Circuits - Hybrid SEED (Self Electro-optic Effect Device)

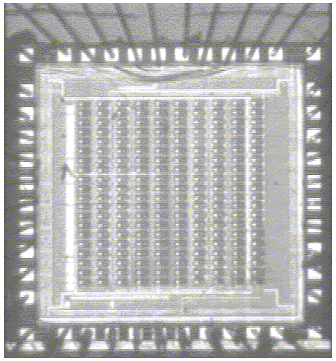


K. W. Goossen et al., IEEE Photonics Tech. Lett. 7, 360 - 362 (1995)

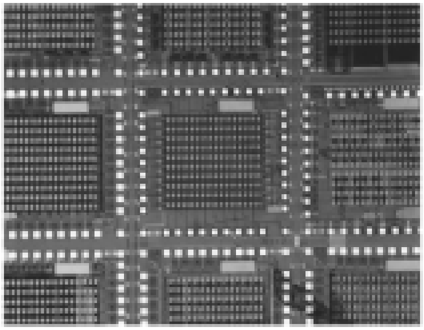
Bell Labs Multiproject OE-VLSI Wafer

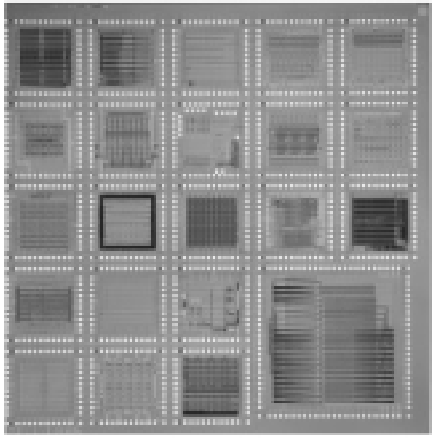


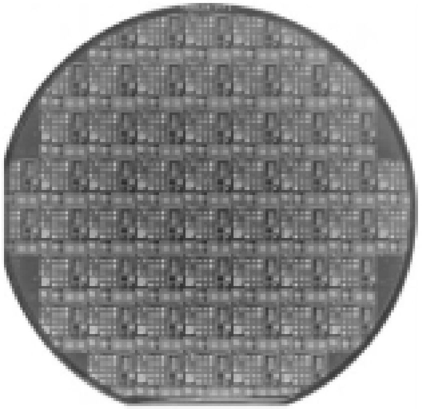




Arrays of solder-bonded multiple quantum well modulator/detector diodes on 0.5 µm Si CMOS

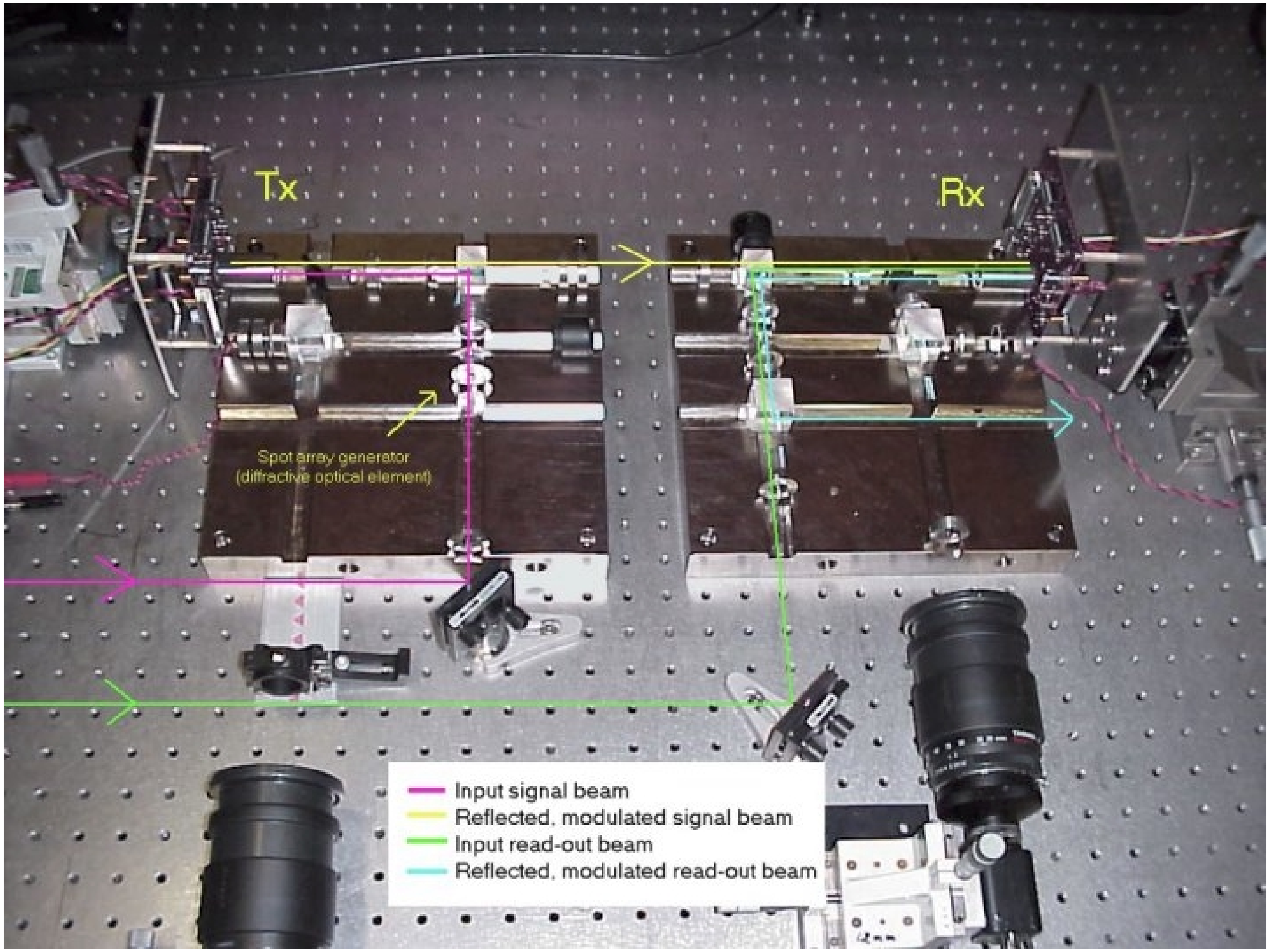




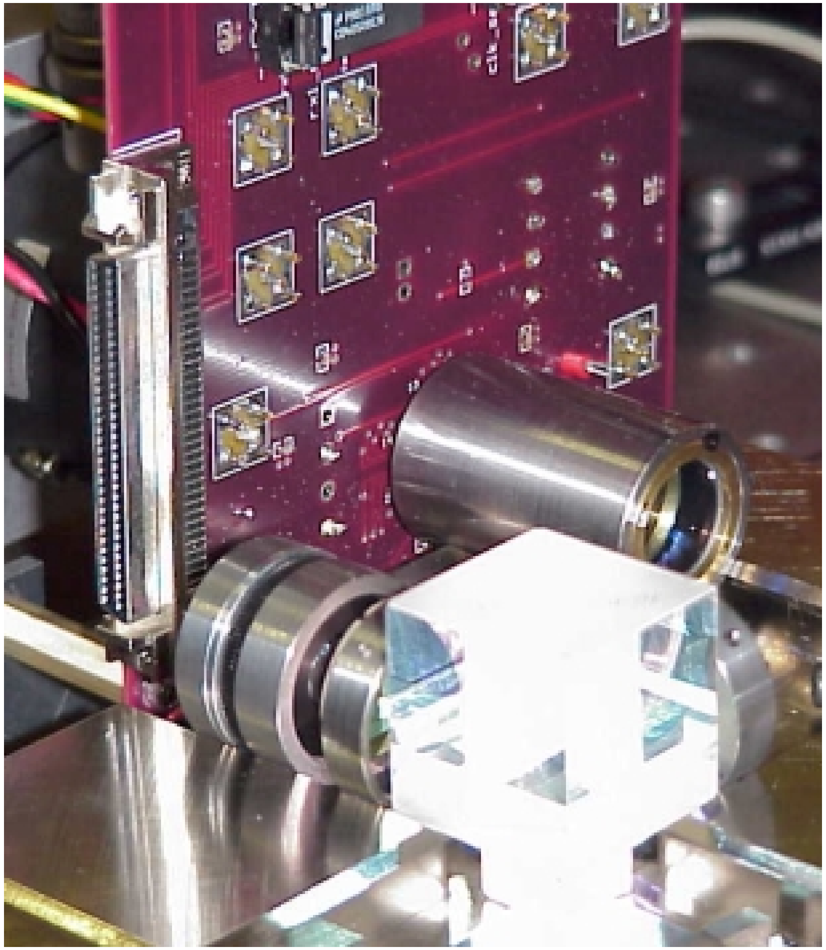


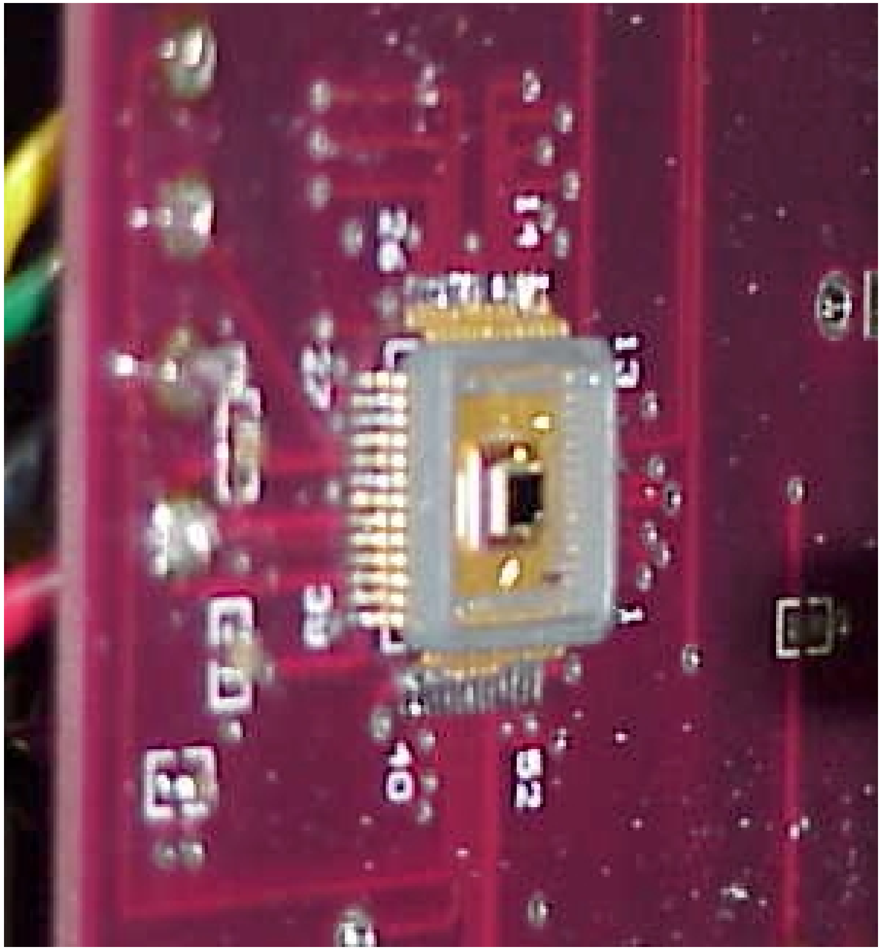
A. V. Krishnamoorthy and K. W. Goossen, IEEE J. Sel. Top. Quantum Electronics 4, 899 (1998)

Baseplate Testing Setup

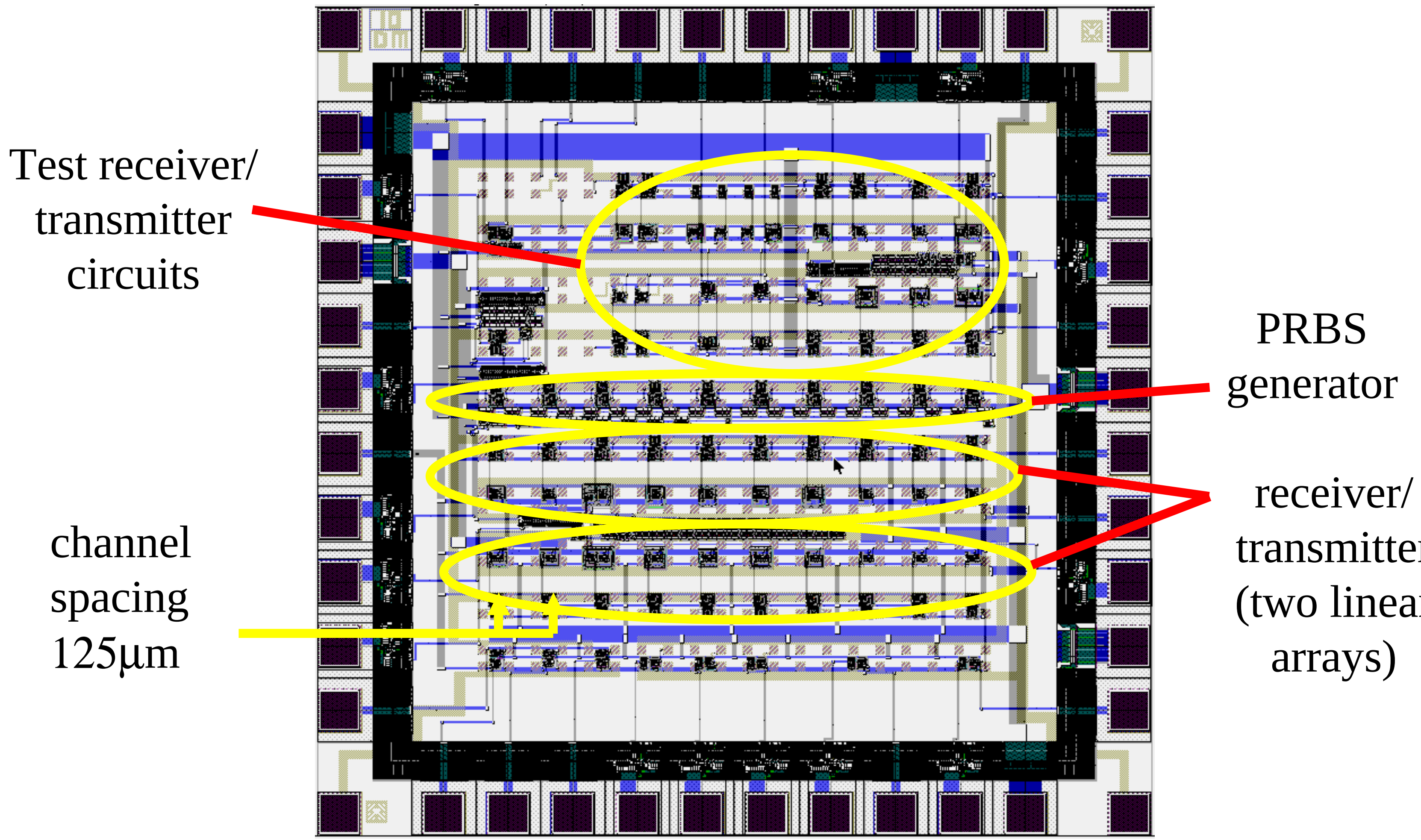


Close-up of Transmitter





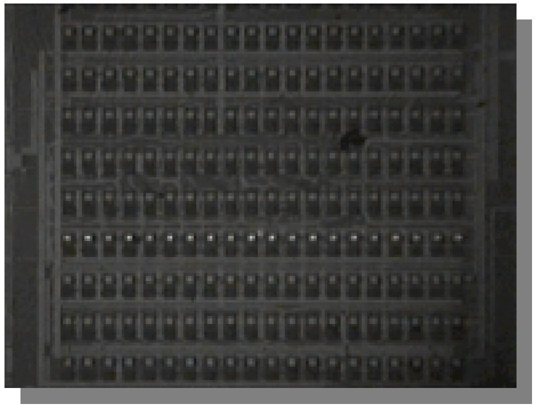
Chip Details



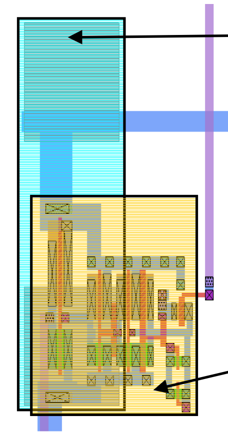
Example linear array optical interconnect

Transmitter chip

Modulator array operating with readout beams from spot array generator



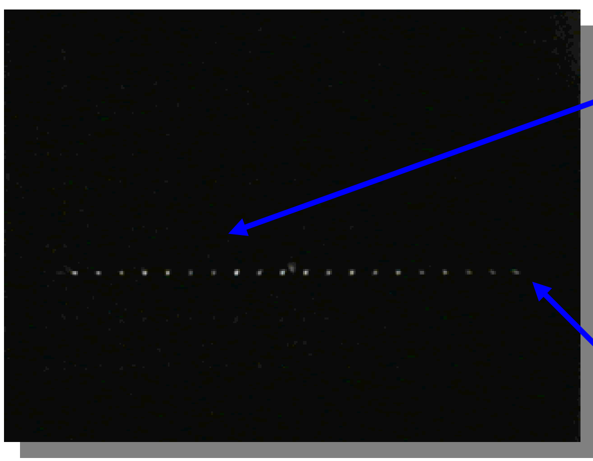
Receiver layout



Photodetector

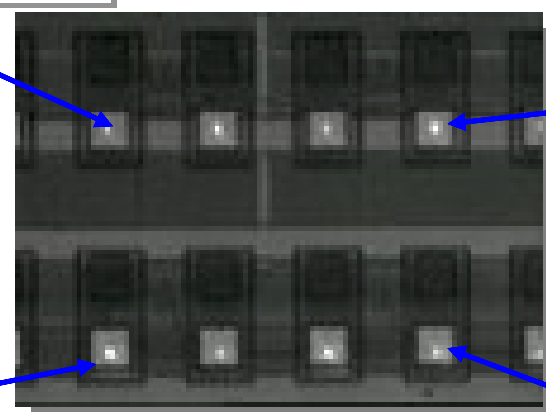
Receiver circuit

Receiver chip



Test optical readout from modulators connected to receiver circuit outputs

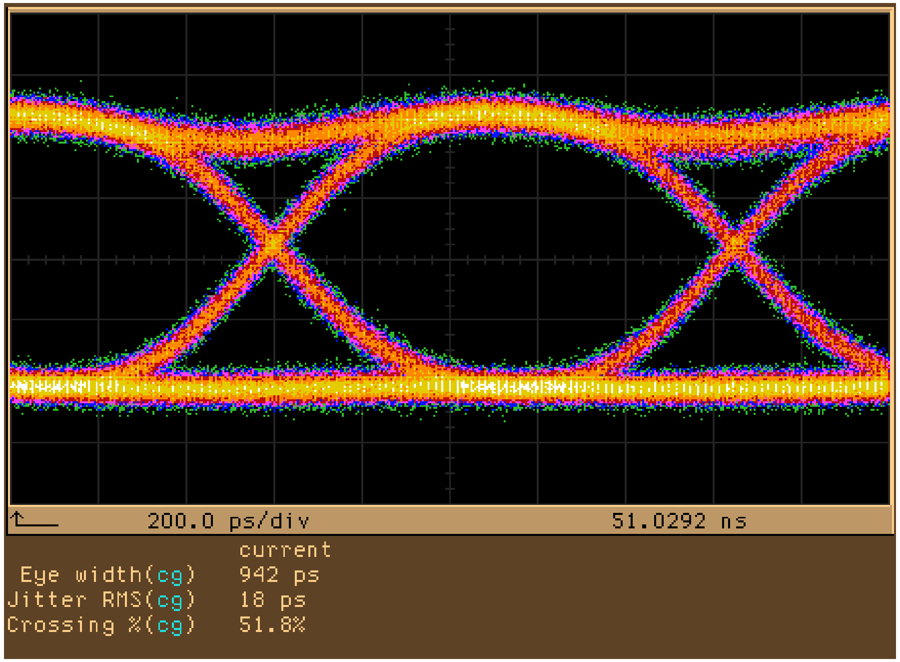
Modulated optical inputs from transmitter chip



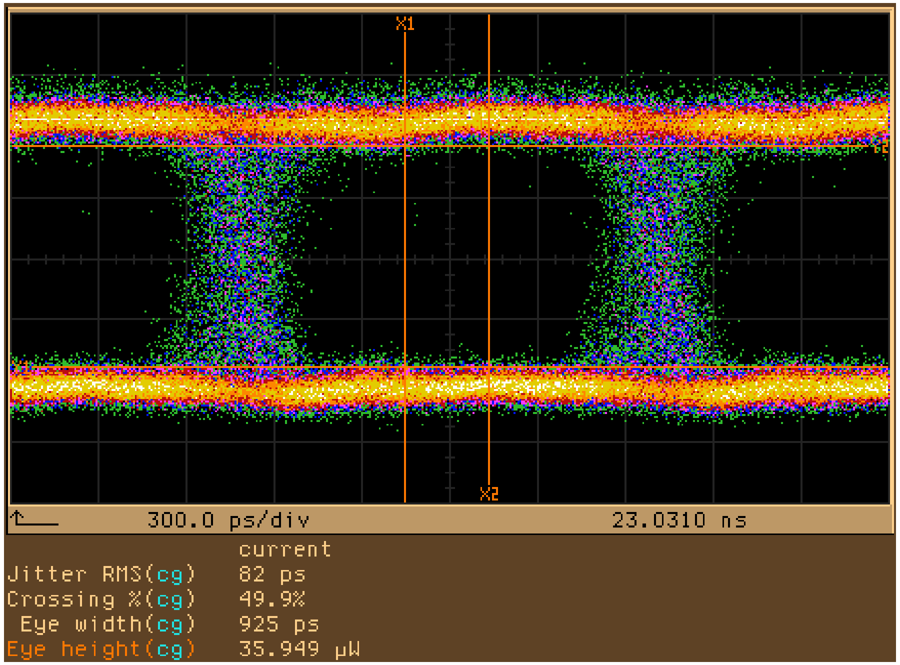
62.5 µm

Receiver array with
- •test output modulators
- • receiver circuits (obscured by photodetectors)
- • photodetectors

Device performance

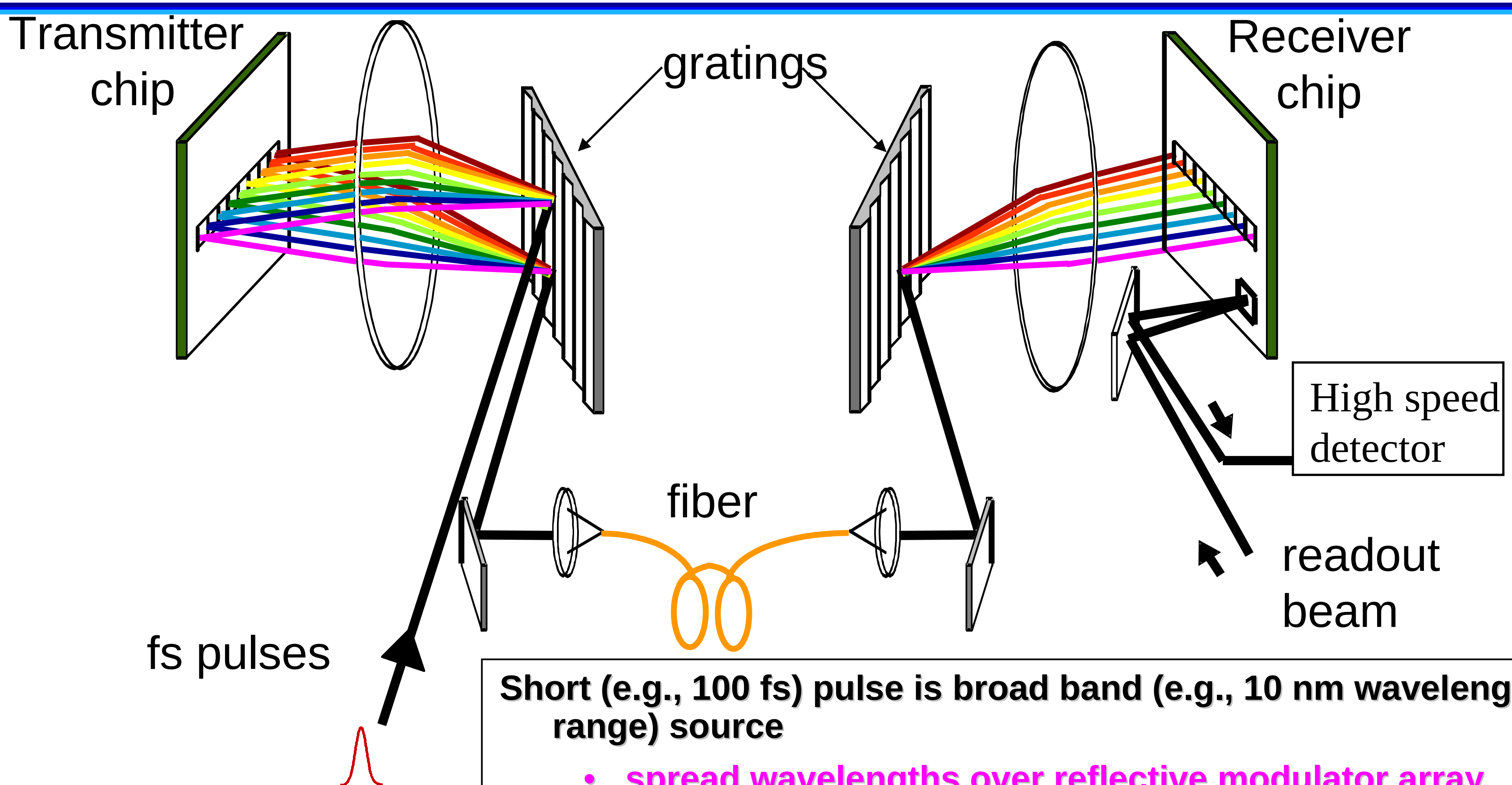


950 Mb/s modulator output with cw readout



700 Mb/s receiver eye diagram using cw laser drive (100 µW optical power per diode)

Short Pulse WDM Interconnect System

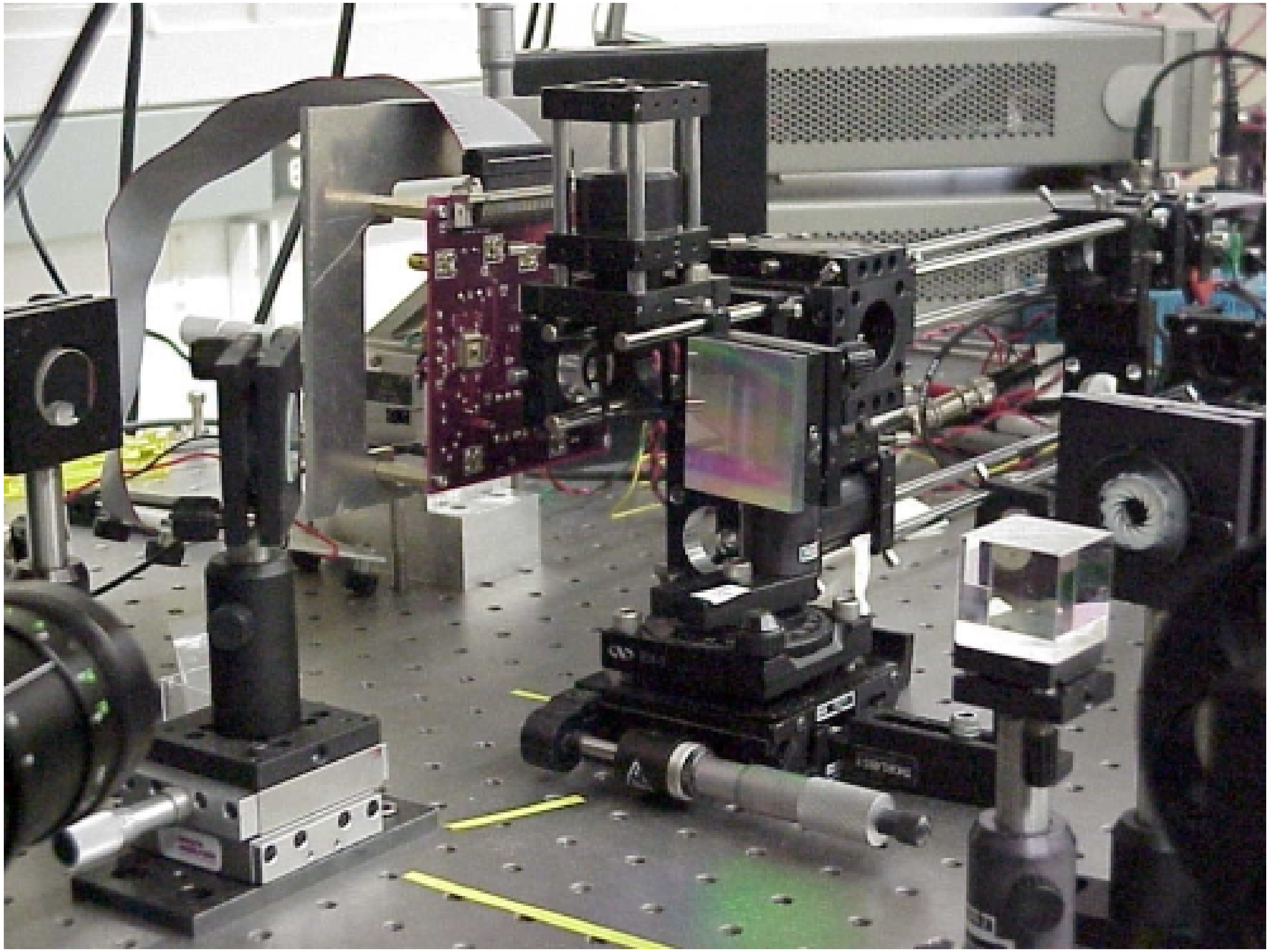


Short (e.g., 100 fs) pulse is broad band (e.g., 10 nm wavelength range) source

- **spread wavelengths over reflective modulator array**
  - **send reflected signals over single fiber to receiver array**

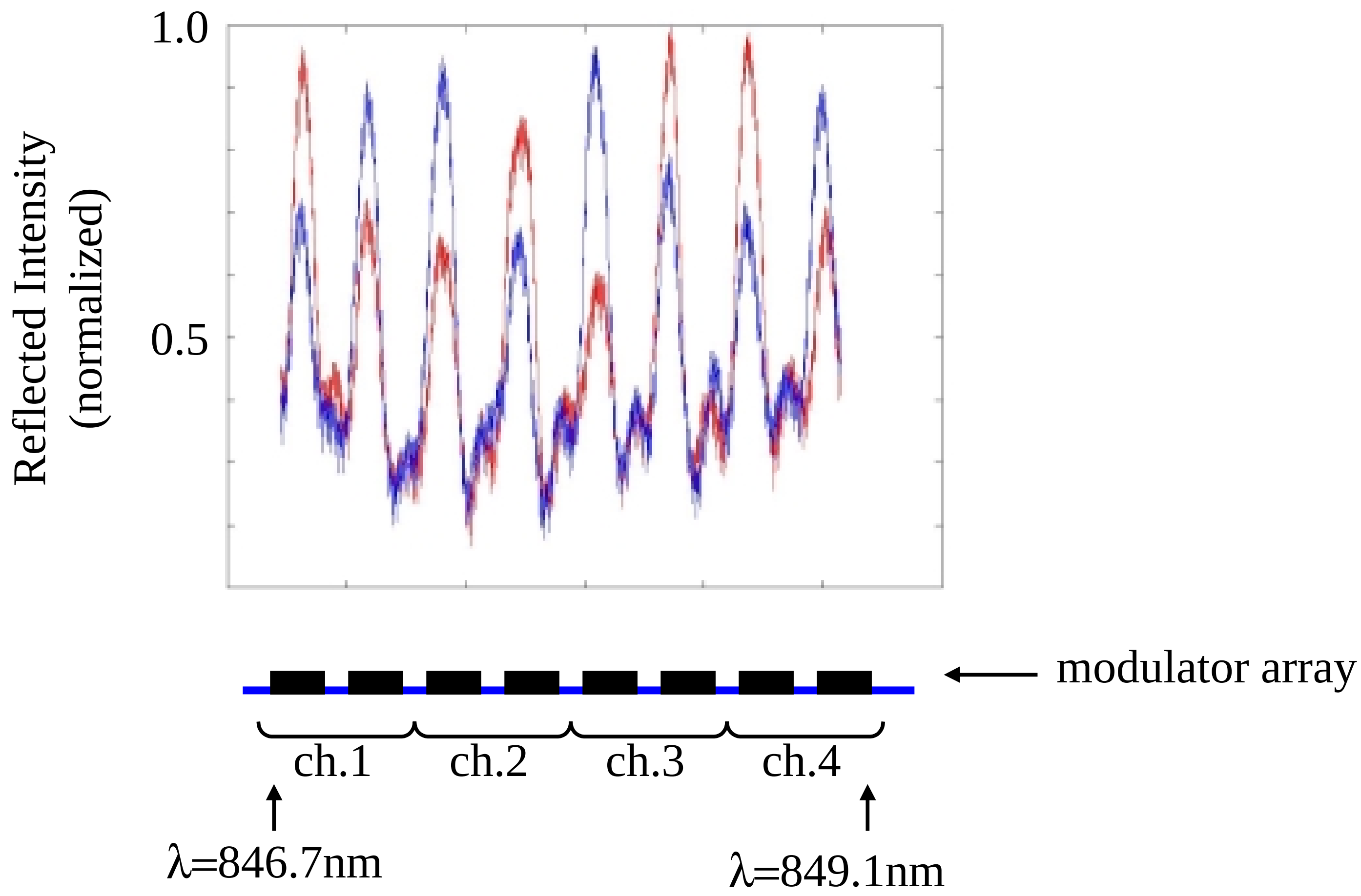
Multiple channel interconnect with single fiber and single laser

WDM Interconnect Setup

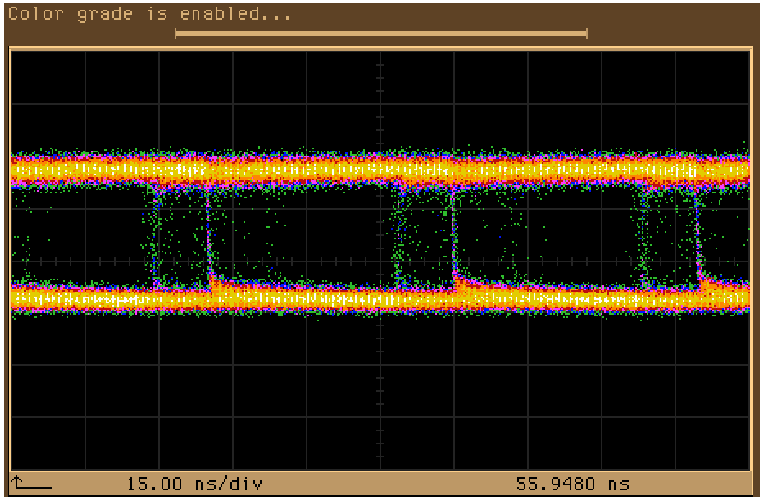


Modulator Array Testing

Modulator array output in Optical Spectrum Analyzer System



Operation of WDM Interconnect



Receiver eye with optical readout

Entire **WDM interconnect system operating at 20 Mbps**

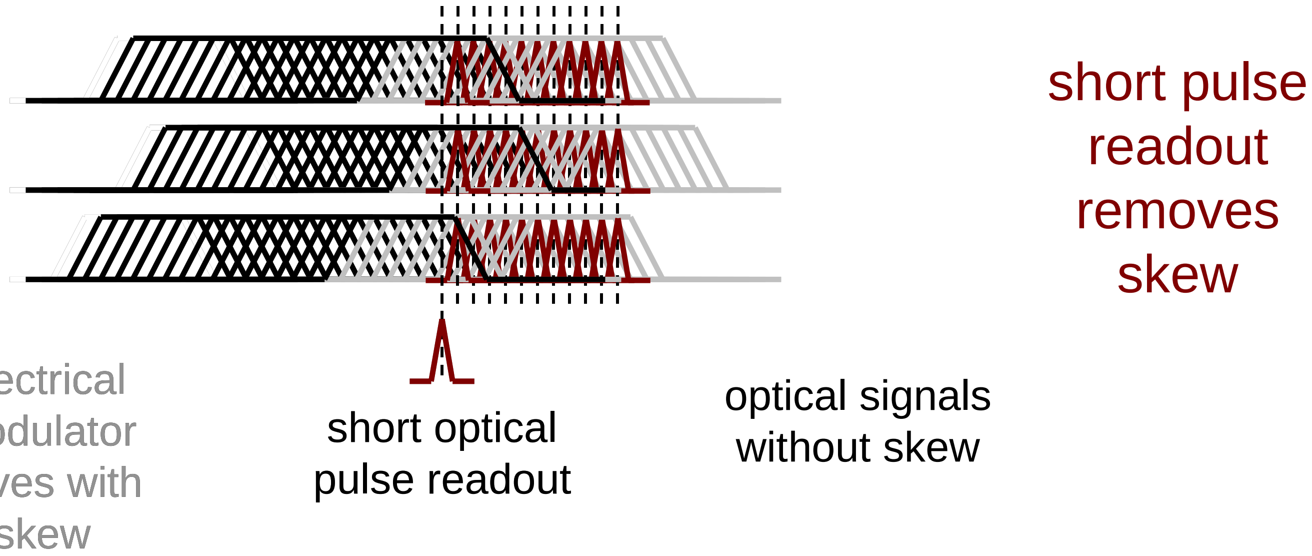
Key issues limiting system performance

- **insufficient uniformity in silicon receiver circuits**
  - ***improved circuits now in fabrication***
- **simple bench-top optomechanics not sufficiently rigid**
  - ***second generation optomechanics now under construction***

Features of short-pulse dense WDM interconnects to silicon chips

- **avoids electronic multiplexing and demultiplexing**
- **uses single laser for multiple channels**
- **uses single fiber for multiple channels**
- **intrinsically synchronizes all channels**
- **exploits all other advantages of short pulse interconnects**

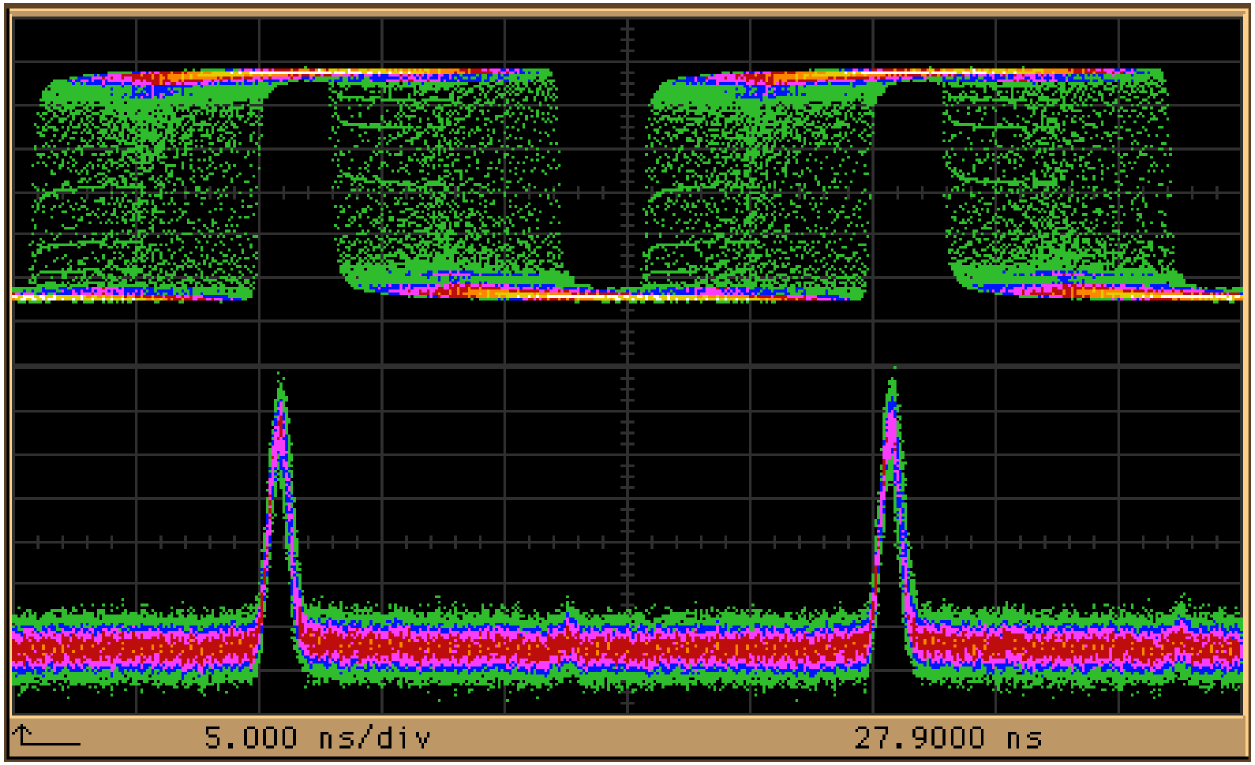
Removal of Skew By Using Short Pulses With Modulators



Effectively sampling the data on modulator

Up to one half bit of skew in modulator drive can be removed

Experimental Demonstration of Jitter Removal with Short Pulses



Electrical input signal to modulator, with jitter

Optical output signal after reading out with a short pulse, receiving the signal, and driving a second modulator

D. Agarwal, G. Keeler, B. Nelson, D. A. B. Miller (Stanford)

Demonstration of jitter removal from a single interconnect channel, at a clock rate of 82 MHz.

GaInAsN for Long-Wavelength Uniform Devices

Growth of this material by MBE shows

- unity sticking coefficient of nitrogen
  - *every nitrogen atom that lands on the surface incorporates, independent of growth rate*

contrasts with strong dependencies of InGaAsP growth on temperature and flux

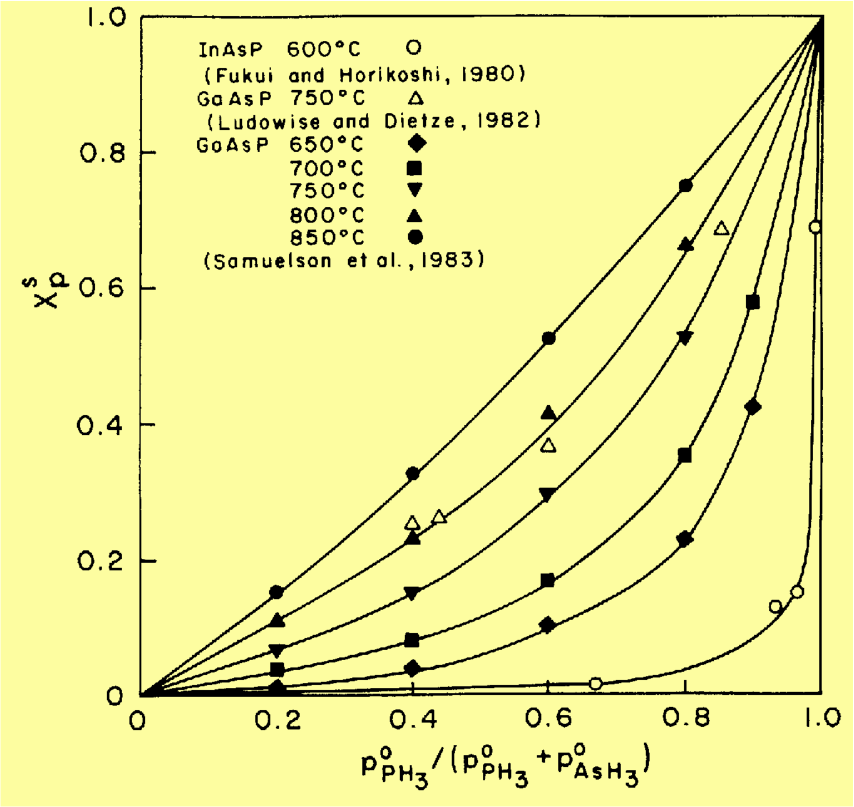
- may allow uniform, reproducible growth of long-wavelength devices

Allows use of GaAs substrates

Demonstrated 1.2 micron CW VCSEL

Possibilities for other, longer wavelength devices

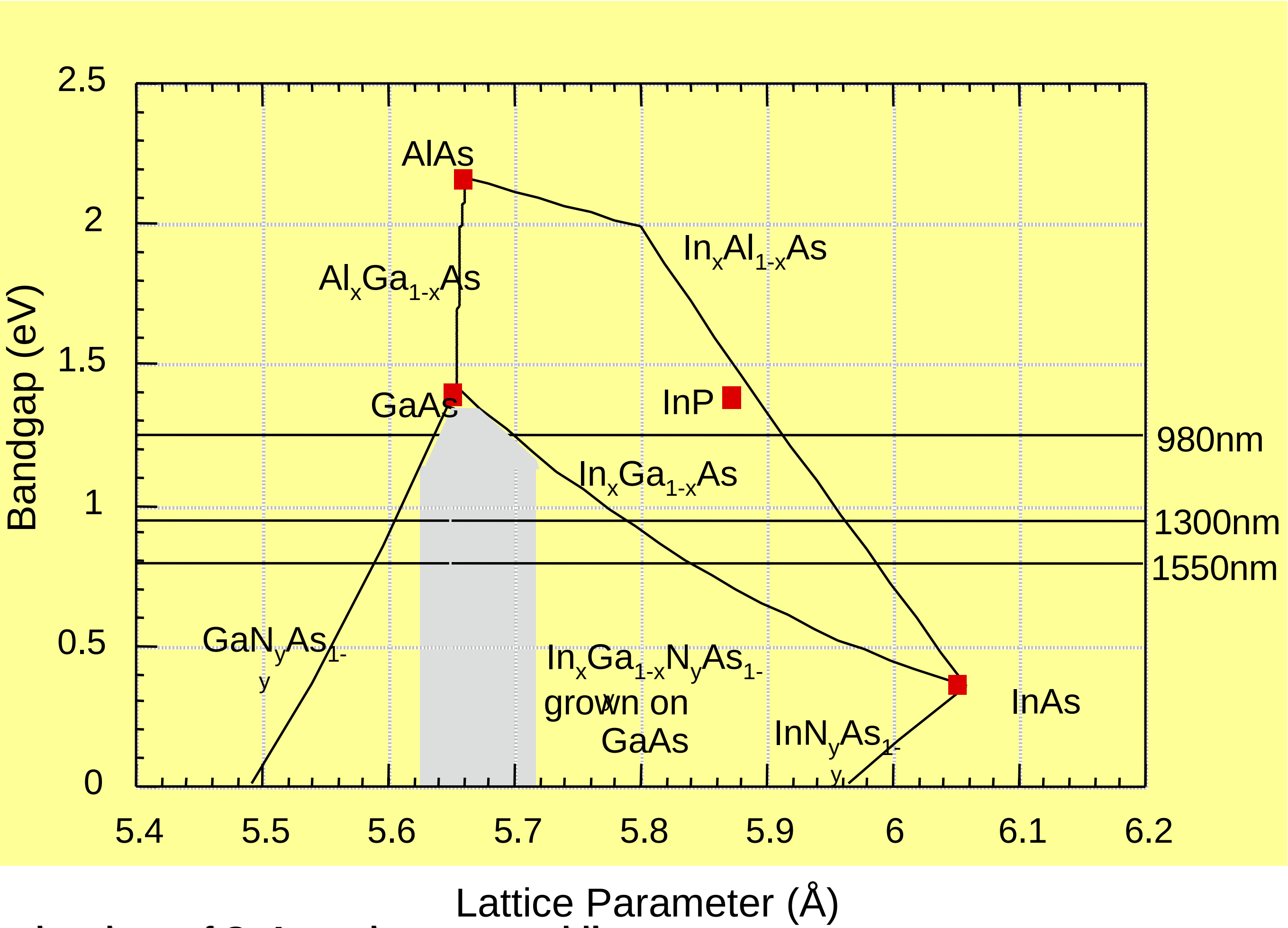
Group V concentration in Arsenide-Phosphides



Stringfellow
Organometallic Vapor-phase Epitaxy
Theory and Practice

Phosphorus concentration (x_P^s): dependent on temperature,dependent on AsH_3 and PH_3 flux because both kinetics (incomplete pyrolysis of the hydrides) and thermodynamics determine concentration.

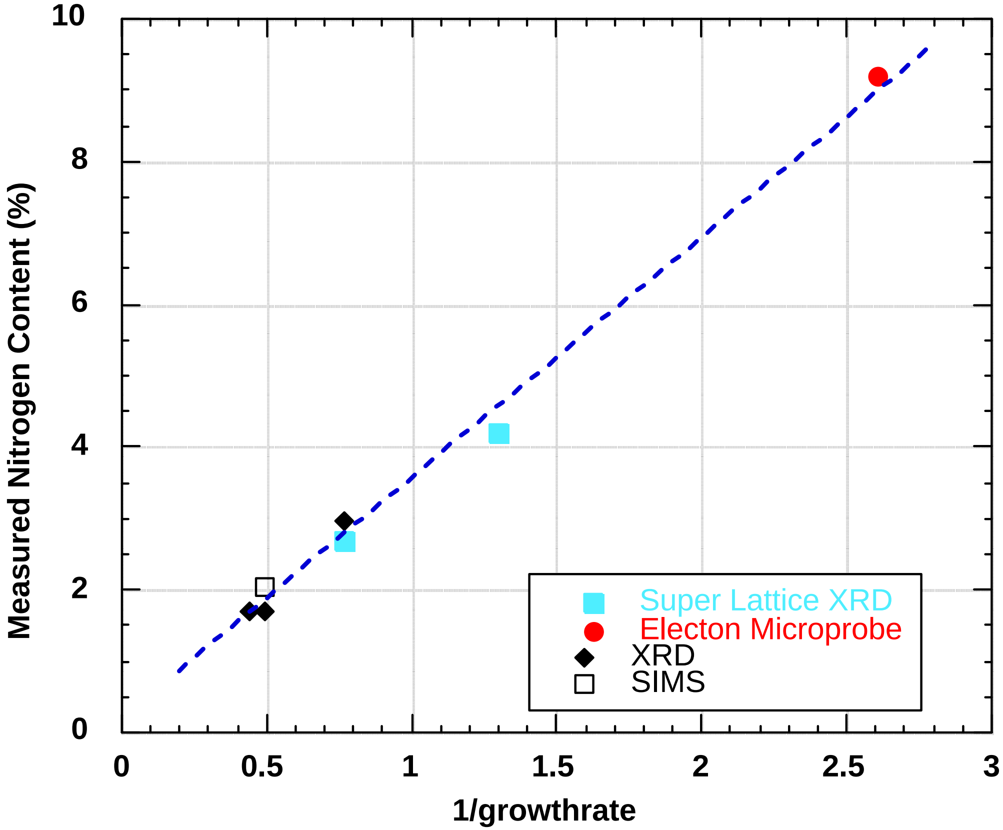
Bandgaps of III-V Alloys



N causes bandgap of GaAs to decrease rapidly.

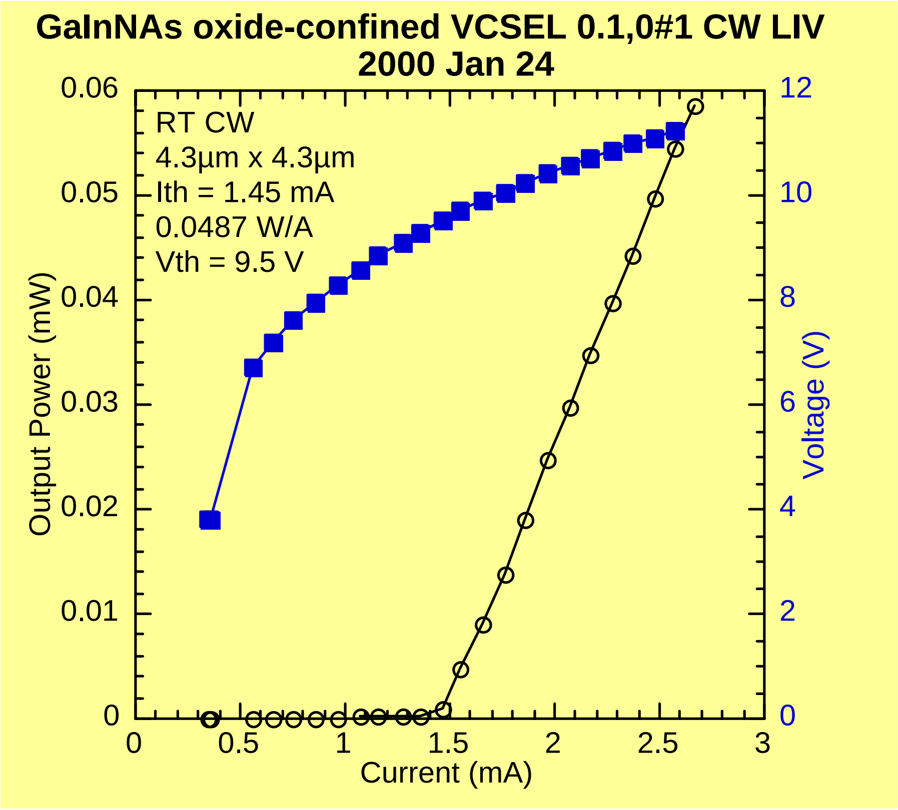
N is small and In is big ⇨ strain can be tuned from tensile to compressive when grown on GaAs.

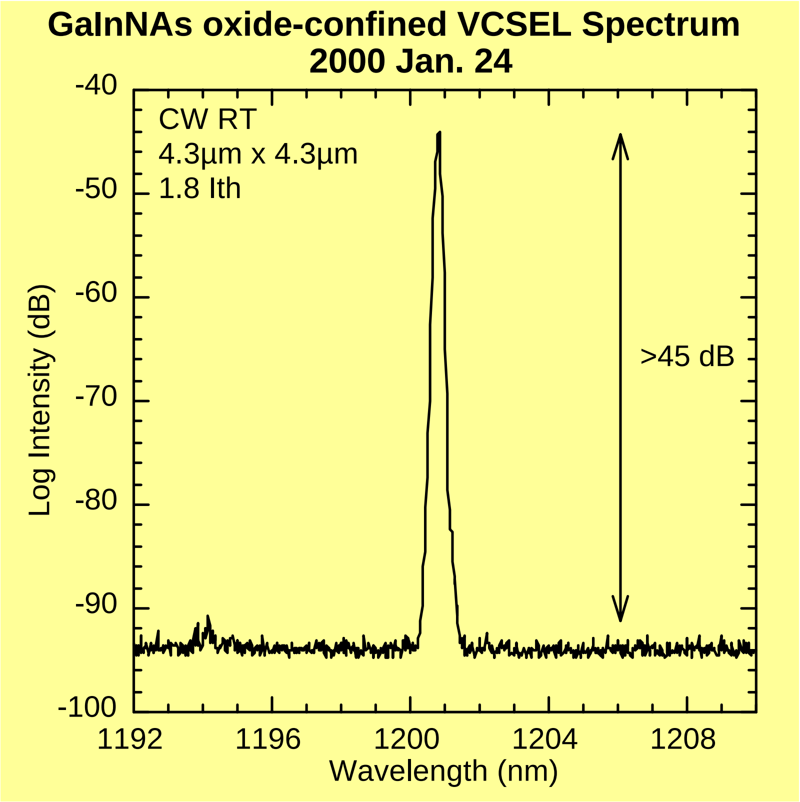
GaInNAs Elemental Source MBE



- **Low substrate temperature avoids phase segregation**
- **Atomic Nitrogen sticking coefficient ~ 1 (N mole fraction =1/growth rate)**
- **Hence expect uniform, predicable growth of this material**

CW operation oxide-confined VCSEL





David A. B. Miller, Stanford

Ultrafast Optoelectronic Gate

Device concept

- trigger top diode to give rise to temporary local voltage change in bottom diode
- voltage change in bottom diode gives temporary change in absorption, modulating beam

Optically-controlled optical gate to transfer data from one beam to another (e.g., different wavelengths)

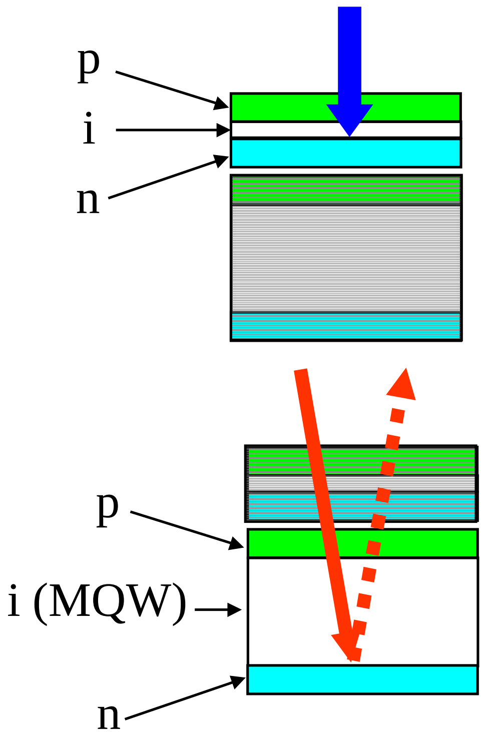
Electrically controlled - only works when diodes are biased

Top Diode

- Thin intrinsic region
- $Al_{0.3}Ga_{0.7}As$, transparent at ~850nm

Bottom Diode

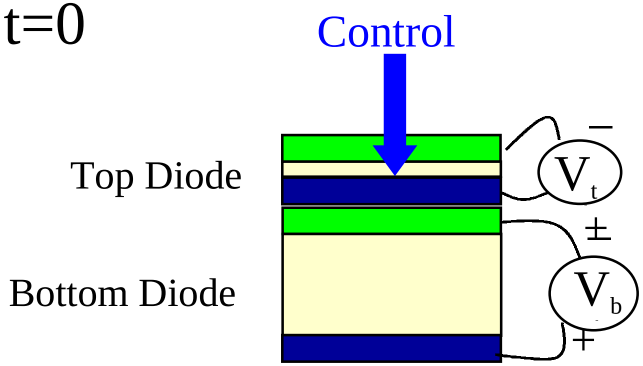
- Thick intrinsic region
- GaAs multiple quantum wells
  voltage-sensitive at ~850nm



David A. B. Miller, Stanford

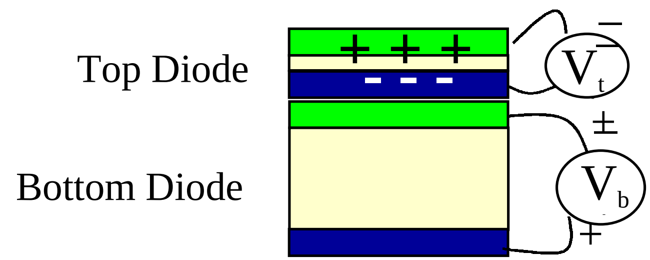
Basic Design Concept

(1) t=0



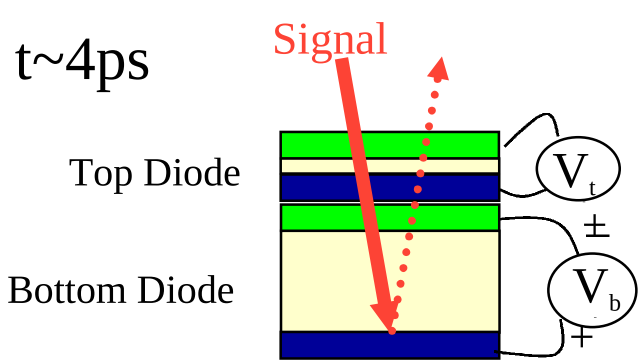
Control pulse is absorbed in top diode

(2) t=0-4ps



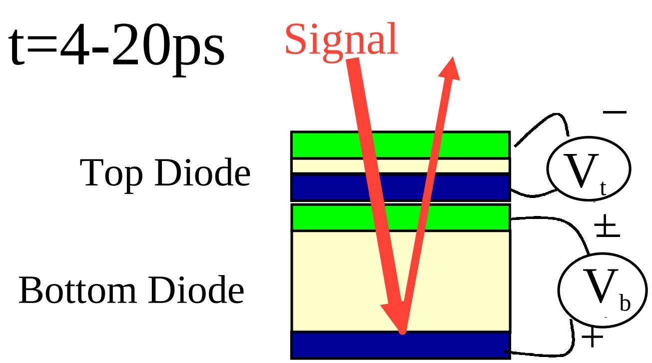
Due to separation of photogenerated carriers, voltage builds up, shielding the bias

(3) t~4ps



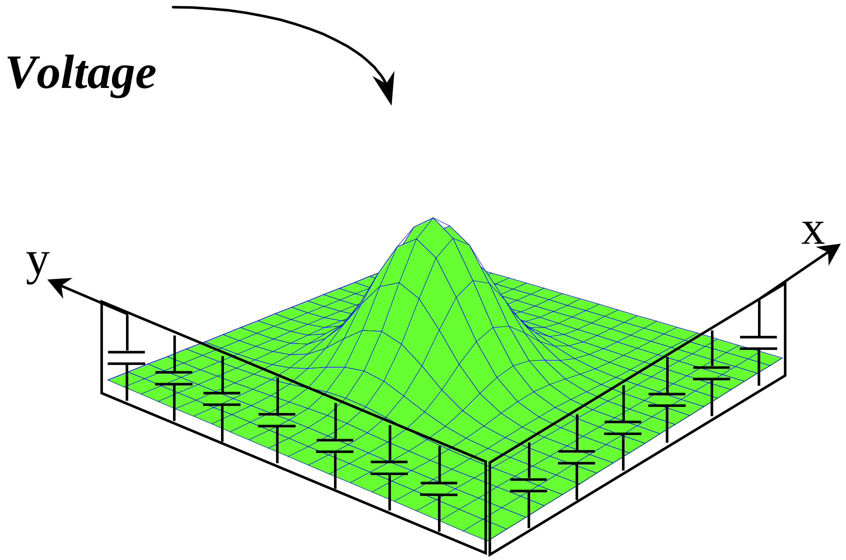
Voltage build-up changes absorption level in bottom diode: ON

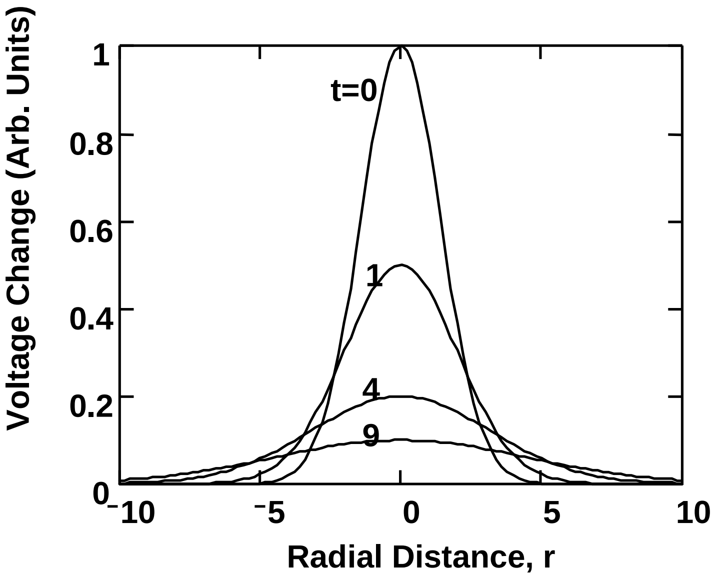
(4) t=4-20ps



Voltage build-up decays away: OFF

Diffusive Conduction



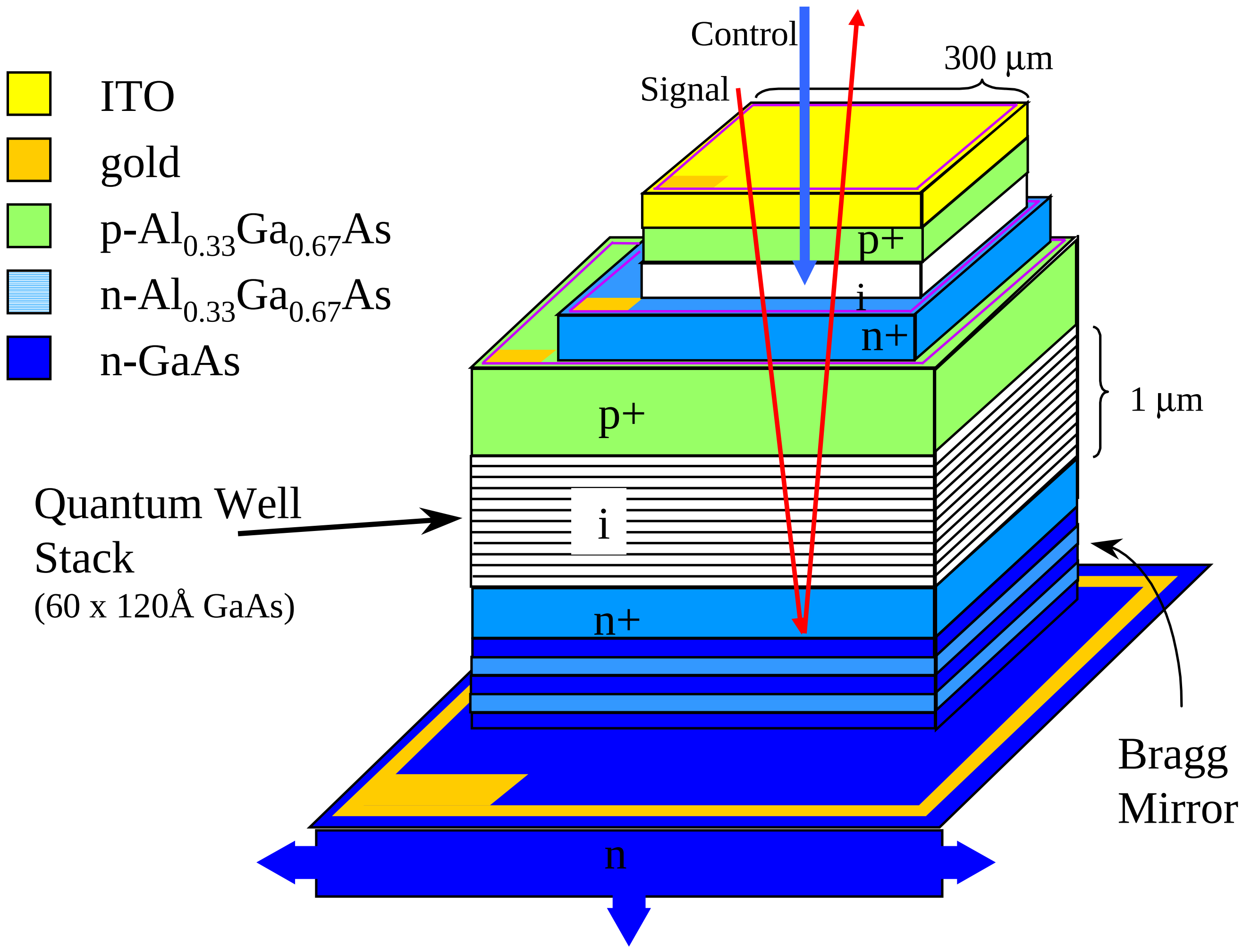


$$\frac{dV}{dt} = D\nabla_{xy}^{2}V$$

$$D = \frac{1}{R_{SQ}C_A}$$

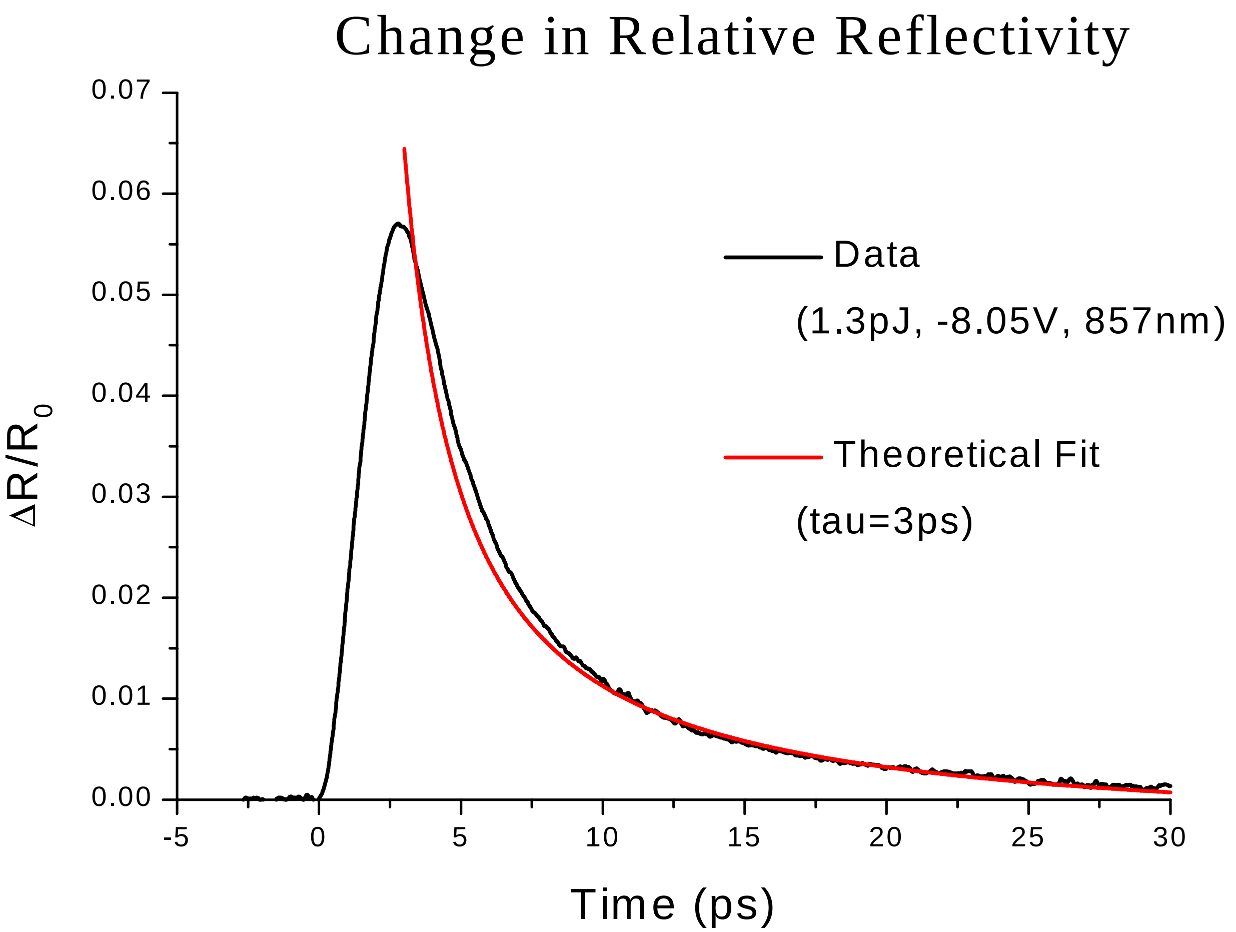
R_{SQ} = Resistance per square
C_A = Capacitance per unit area

Device Structure



David A. B. Miller, Stanford

Results



Change in Relative Reflectivity
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
ΔR/R0
-5
0
5
10
15
20
25
30
Time (ps)
Data
(1.3pJ, -8.05V, 857nm)
Theoretical Fit
(tau=3ps)

Results: Large Signal Response

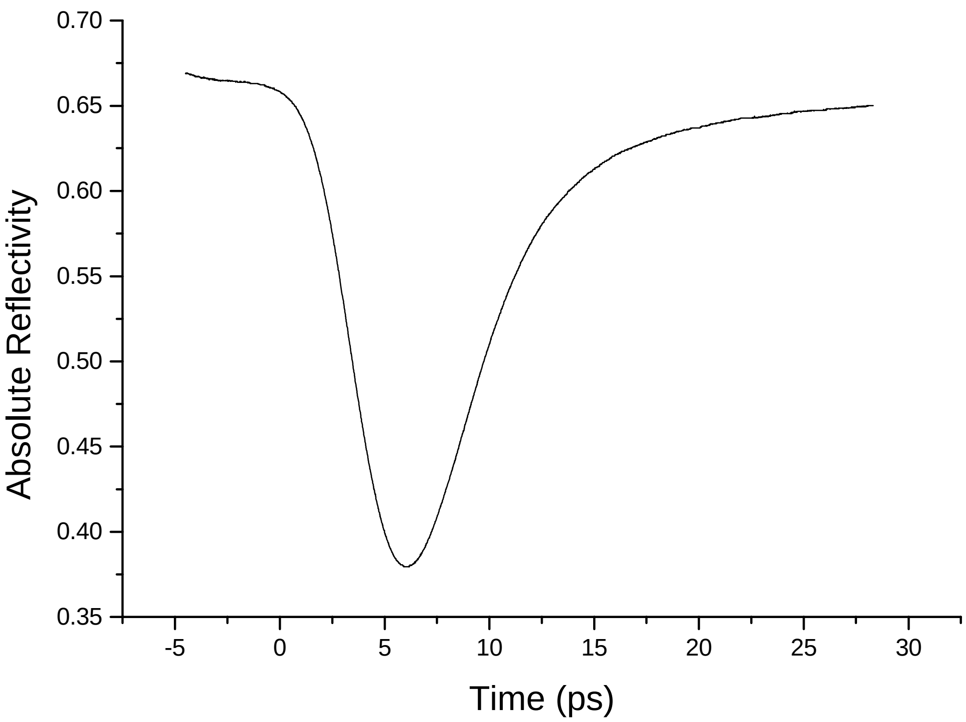
Description:

- **3.5μm spot radius**
- **1.5 pJ/pulse**
- **39 fJ/μm^2**
- **2 ps pulse width**

20 ps FW-10%M

30% Reflectivity Change

Nearly 2-to-1 Contrast Ratio

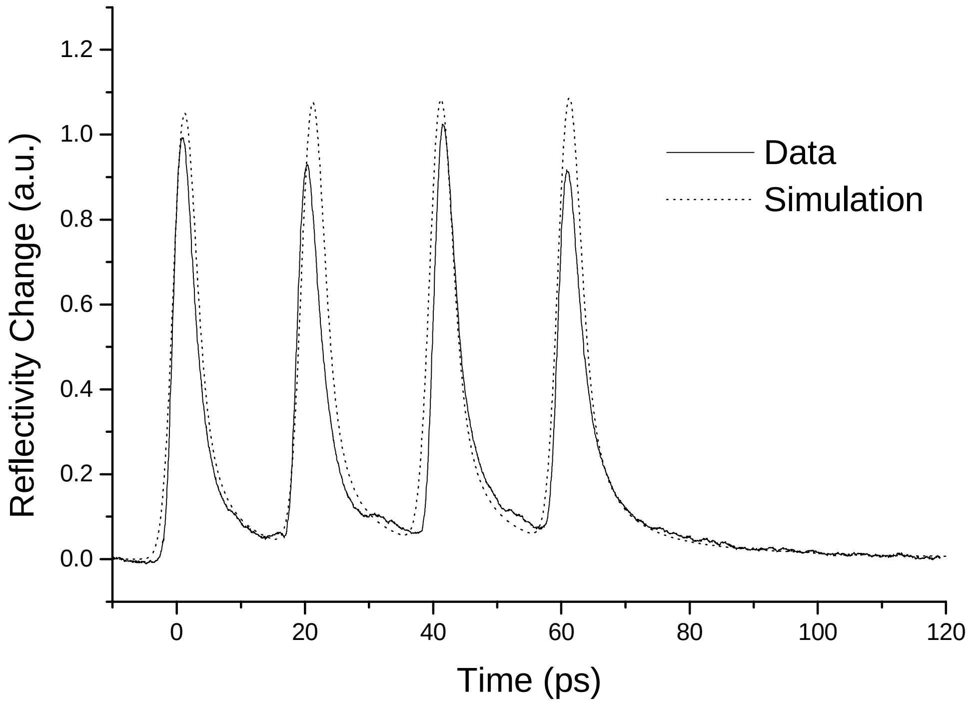


David A. B. Miller, Stanford

Results: Pulse Repetition Response

Description:

- **3.5 μm spot radius**
- **20 ps pulse separation**
- **2 ps pulse length**
- **~ 70 fJ/pulse**



Conclusions

- WDM interconnect between silicon chips successfully demonstrated
- Synchronization of signals using short optical pulses
- GaInAsN promising material for uniform long-wavelength devices, with cw VCSEL demonstrated
- Ultrafast optically controlled optical gate may allow fast, digital, electrially-controllable wavelength converting and switching devices